Preprint
UCRL-JC-152261

Shock-Dispersed-Fuel Charges-Combustion in Chambers and Tunnels

P. Neuwald, H. Reichenbach, A. L. Kuhl

This article was submitted to
34th International ICT Conference: Energetic Materials: Reactions of Propellants, Explosives and Pyrotechnics, Karlsruhe, Germany, June 24-27, 2003

April 23, 2003

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

This work was performed under the auspices of the United States Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

34th International ICT-Conference, Karlsruhe, 2003
Energetic Materials – Reactions of Propellants, Explosives and Pyrotechnics

SHOCK-DISPERSED-FUEL CHARGES – COMBUSTION IN CHAMBERS AND TUNNELS

Peter Neuwald and Heinz Reichenbach
Fraunhofer-Institut für Kurzzeitdynamik – Ernst-Mach-Institut –
Eckerstr. 4, 79104 Freiburg i. Br., Germany

Allen L. Kuhl
Lawrence Livermore National Laboratory
7000 East Avenue, Livermore, CA, USA, 94551-0808

Abstract

In previous studies we have investigated after-burning effects of a fuel-rich explosive (TNT). In that case the detonation only releases about 30 % of the available energy but generates a hot cloud of fuel that can burn in the ambient air, thus evoking an additional energy release that is distributed in space and time. The current series of small-scale experiments can be looked upon as a natural generalization of this mechanism: a booster charge disperses a (non-explosive) fuel, provides mixing with air and – by means of the hot detonation products – energy to ignite the fuel.

The current version of our miniature Shock-Dispersed-Fuel (SDF) charges consists of a spherical booster charge of 0.5 g PETN, embedded in a paper cylinder of approximately 2.2 cm^3, which is filled with powdered fuel compositions. The main compositions studied up to now contain aluminum powder, hydrocarbon powders like polyethylene or sucrose and/or carbon particles. These charges were studied in three different chambers of 4-l, 6.6-l and 40.5-l volume and the small-scale model of a closed tunnel section.

In general, the booster charge was sufficient to initiate burning of the fuel. This modifies the pressure signatures measured with a number of wall gages and increases the quasi-static overpressure level obtained in the chambers. The time-scale and the yield of the pressure rise depend on the fuel and its characteristics, but largely also on the flow dynamics in the chamber, which is dominated by shock reverberations, and thus on the chamber geometry and volume.

Correspondence to
Dr. Peter Neuwald, – Ernst-Mach-Institut – Fraunhofer-Institut für Kurzzeitdynamik,
Eckerstr. 4, 79104 Freiburg i. Br., Germany
Tel. +49 (0) 761/2714-324, Fax +49 (0) 761/2714-316, e-mail : neuwald@emi.fraunhofer.de

Introduction

For about two decades the experimental fluid dynamics group of the Ernst-Mach-Institute has investigated blast phenomena at laboratory scale. Much of this work has been motivated by our collaboration with parts of the CFD-community and aims at providing experimental data for code evaluation and insight into the phenomenology of specific scenarios. Along with the increasing capabilities of numerical simulation the topics of interest have broadened beyond classical problems like blast attenuation and blast loads on structures and now include explosively induced combustion processes. This subject area can be roughly divided into two sub-topics: combustion as a collateral effect of a detonating charge, when flammable materials are subjected to the blast, and combustion as an inherent effect of the explosive or the charge. Representative of the latter is the issue of after-burning of TNT. Here the detonation creates a hot cloud of combustible gaseous fuel (the detonation products). The fuel cloud is subjected to the flow-field generated by the detonation, eventually gets mixed with the ambient air and can thus release additional energy by means of combustion. The current series of small-scale experiments can be looked upon as a natural generalization of the after-burning concept. The basic idea behind this generalization is: if combustion is to be considered as a relevant energy source in the aftereffects of a charge detonation, it is not necessarily the detonation products from the explosive that have to constitute the fuel. Other flammable (non-explosive) substances might generate similar effects when dispersed by a detonation. The effects could even be more pronounced, since a number of substances outmatch TNT in terms of the heat of combustion. This line of thought led to the development of what we call Shock-Dispersed-Fuel (SDF) charges. The design of this charge type will be discussed below.

Design of Small-Scale Charges in the 1-g Range

The basis of all charge types discussed in this paper are custom made spherical small-scale PETN-charges. They consist of nearly pure PETN at a density of about 1 g/cm³. Two electrical ignition wires are embedded. A thin resistance wire at the top bridges the small gap between these wires. Care is being taken that the resistance wire is located in the center of the explosive sphere. A high voltage discharge explodes the bridge wire. This explosion drives the detonation through the charge. In laboratory experiments we typically use charges with masses from 0.2 g to approximately 1.5 g.

PETN exhibits negligible after-burning. It is well, albeit not perfectly, oxygen balanced. Its heat of detonation amounts to 6.28 kJ/g, which is 76.5% of its heat of combustion, the value being 8.19 kJ/g [1, 2]. To enhance the after-burning effects EMI has designed a composite TNT-PETN charge. A spherical PETN charge of 0.5 g constitutes the core of the composite charge. The core is repeatedly dipped into molten TNT and dried. Thus an outer shell of TNT forms. Its density is also around 1 g/cm³. For our experiments charges with three different shell masses were manufactured: 0.5 g, 0.7 g and 1 g.

The SDF charges finally consist of a lightweight paper cylinder with a height and diameter of 14 mm. Again a spherical PETN charge of 0.5 g is inserted into the center of the cylinder. It acts as the dispersing booster. The remaining volume (1.6 cm³) of the cylinder is filled with the fuel to be dispersed. The fuels of our choice for this exploratory test series were readily available powders of aluminum, hydrocarbons like sucrose (labeled HC in plots) or polyethylene (PE), carbon or mixtures of these. The cylinder holds fuel masses from 0.65 g to 1.1 g depending on the density of the powders. We have also substituted these non-explosives fuels by PETN or TNT powder.

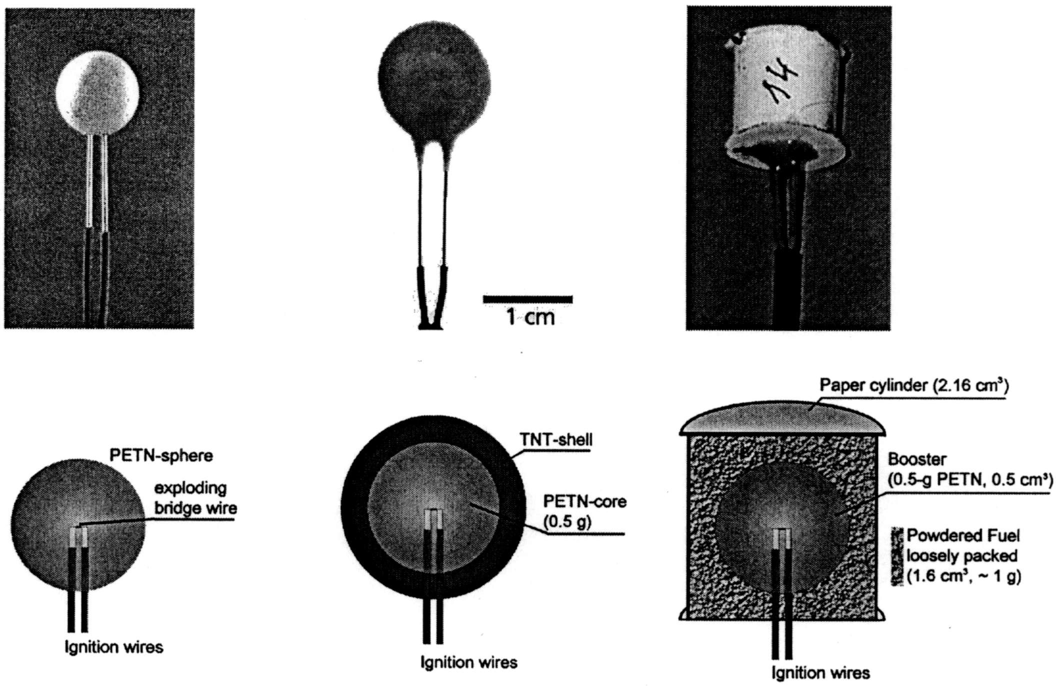

Figure 1
Top row: Photographs of a spherical PETN charge, a composite TNT charge and an SDF charge.
Bottom row: Schematic sketches of the charge designs.

Particulate size certainly plays an important role in the combustion of the dispersed fuels. The aluminum powder came in form of thin flakes (thickness in the order of 2 µm) with a wide distribution of sizes seen in the SEM image in Figure 2. The carbon powder (or more exactly activated charcoal ground in a ball mill) was passed through a set of sieves. Thus we gained samples with a mean particle diameter of 56 µm. The coarsest powder was polyethylene (PE) with granules ranging from 0.1 to 1 mm in diameter (Figure 3). According to the manufacturer the average particle diameter is around 350 µm.

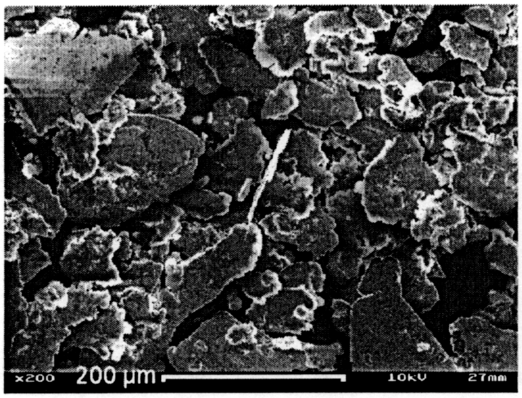

Figure 2
SEM image of the aluminum flakes.

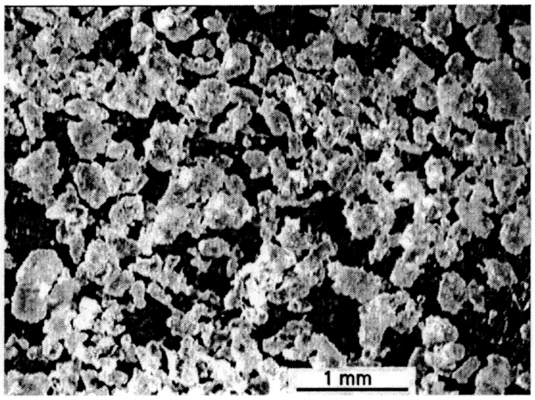

Figure 3
Microscopic image of the PE granules.

Feasibility Tests in a 4-l Chamber

Initial feasibility studies were performed in a rectangular chamber of approximately 4 l inner volume and dimensions of 101.5mm x 101.5 mm x 386 mm. The sidewalls consisted of transparent Makrolon plates which gave optical access to the chamber. A high-speed video camera was used to monitor the combustion. In addition, a number of piezo-electric pressure gages in the chamber walls measured the transient and quasi-static overpressures due to blast reverberations and combustion. The feasibility experiments are discussed in greater detail in [3]. To summarize the findings: all tested powders or powder mixtures were ignited subsequently to the detonation and generated quasi-static overpressures in excess of the pressure caused by the detonation of a bare booster charge. The most rapid reaction was found for charges filled with a mixture of 40% aluminum flakes and 60% sucrose powder (pure aluminum flakes were not tested in the feasibility study). The maximum overpressure value was obtained within the first two milliseconds after the detonation. A filling of pure carbon powder resulted in a much slower combustion; it took about 15 ms until the maximum in the quasi-static overpressure was obtained. The video sequence from the tests affirm the differences in the combustion dynamics: In the case of the aluminum-sucrose mixture the detonation flash rapidly develops into a growing self-luminous region which spreads over nearly the whole chamber within 500 µs. In contrast, the luminosity initially drops for the test with pure carbon powder, until two hot spots form at about 600 µs, which grow at a much lower rate. An interesting phenomenon could be observed in a test where the SDF charge was filled with pure sucrose powder: while again initially the luminosity drops, it is drastically enhanced at 500 µs in strongly localized and structured band-like region. Presumably this region corresponds to a region where the interaction between reflected shocks compresses and reheats the fuel-air mixture.

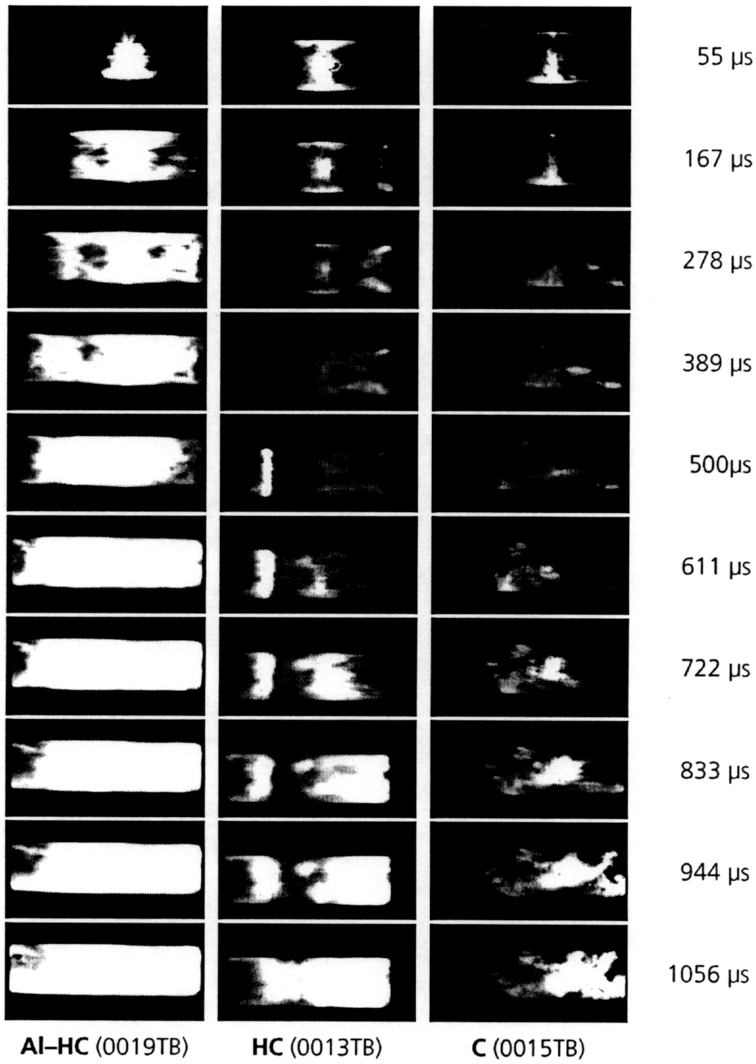

Figure 4
Series of video frames showing the combustion of three types of shock-dispersed fuel in the 4-l chamber.

Tests in a Cylindrical 6.6-l Vessel

The 4-l chamber contains too little oxygen to allow complete combustion for most of the SDF charges. Thus the experiments were continued in a cylindrical steel vessel with an inner diameter of 200 mm and a height of 210 mm (inner volume about 6.6 l). The charges were detonated in the center of the vessel; the top lid was instrumented with 8 piezo-electric pressure gages and 1 piezo-resistive gage. The primary blast arrives at the walls after about 75 μs and sets up strong reverberations. Some details for two tests with a bare booster and an SDF charge containing about 1 g aluminum flakes are shown in Figure 5.

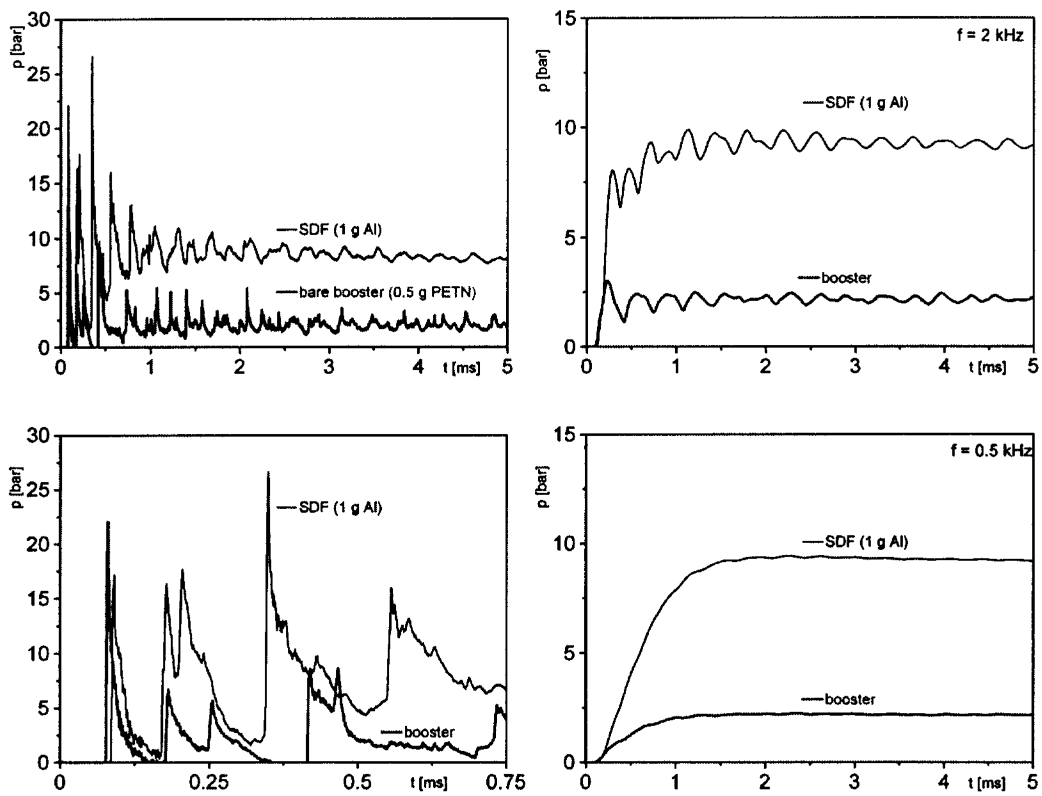

Figure 5
Overpressure vs. time in the 6.6-l cylinder. Left column: record at a piezo-electric gage in the top lid at a distance of 50 mm from the cylinder axis. Right column: record from the piezo-resistive gage in the top lid at a distance of 75 mm from the cylinder axis. Data low-pass filtered at a cut-off frequency of 2 kHz (top) or 0.5 kHz (bottom). Charges: a bare booster of 0.5 g PETN and an SDF charge filled with 1 g aluminum flakes.

The top left plot gives an impression on the strong initial shocks in the vessel, which are superimposed to the rise in the quasi-static overpressure. To enhance the readability in terms of the quasi-static overpressure the plots in the left column present low-pass filtered data. At a cut-off frequency of 2 kHz remainders of the shock reverberation structure are still visible. A cut-off frequency of 0.5 kHz yields smooth curves that allow to determine the attained maximum overpressure level. But the low cut-off frequency falsifies the initial pressure rise rate. However, the plots show the following:

(a) An appreciable part of the overpressure generated by the SDF charge has to be due to the combustion of the aluminum flakes

(b) The maximum overpressure is attained within less than 1.5 ms and about 70% of the additional pressure is generated within the first 0.5 ms.

The bottom left plot in Figure 5 zooms in to the initial 0.75 ms after the detonation. The primary blast wave from the bare booster charge arrives at 77 μs at the gage and has a peak overpressure of about 22 bar. The primary blast from the SDF charge arrives somewhat retarded at 85.5 μs with a smaller peak pressure of about 17.5 bar. This difference can be explained as follows: the paper cylinder and its filling initially act as an inert containment that has to be disrupted by the detonation, thus causing the retardation and attenuation of the generated blast wave. However, the average pressure in the time interval from t = 75 μs to t = 170 μs has a somewhat larger value of about 3.75 bar for the SDF charge compared to 3.1 bar for the bare booster. About another 100 μs after the primary blast the first reflected wave arrives at the gage. Its strength is noticeably larger for the SDF charge and it is obvious that the blast from the SDF charge contains more overpressure impulse than the blast from the booster. The average pressure in the interval from t = 165 μs to t = 320 μs has a value of 7.5 bar for the SDF charge and a value of 2.4 bar for the bare booster. In addition, subsequent wave reflections arrive earlier at the gage for the case of the SDF charge indicating an increase in the propagation velocities.

In summary: the energy release from the combustion of the shock-dispersed aluminum flakes manifests itself clearly in an increase of the quasi-static overpressure generated in the vessel. The energy release is not fast enough to couple into the strength of the primary blast before it arrives at the walls but switches in rapidly enough to become noticeable at times around 200 to 300 μs. The initially rapid pressure rise fades until a final overpressure level around 9.3 bar is attained after less than 1.5 ms. The combustion also modifies the conditions for the blast propagation in the vessel, presumably by an increase of the temperature that causes a higher propagation velocity.

The question arises whether the maximum level of the quasi-static overpressure provides information on the completeness of the combustion. A theoretical estimate was derived from the hypothesis of a constant-volume explosion [4] where the reactants consist of the PETN, the shock-dispersed fuel and air in the correct amounts. For the SDF charge containing aluminum this yields a theoretical value around 9.7 bar which is 4.5% in excess of the experimentally found pressure level. For the bare booster the estimate has a value of about 2.1 bar. The same value was observed experimentally. Thus the assumption of a constant-volume explosion appears to give a reasonable estimate for the global characteristics of the system and we can conclude that the combustion of aluminum from the SDF charge was nearly complete. A more concise analysis of the thermodynamics of TNT after-burning and the combustion of a number of SDF charges is given in [5].

A number of SDF charges with different fuel compositions were tested in the 6.6-l cylinder. The results for the quasi-static overpressure levels are summarized in Figure 6. It shows that the SDF charges in general generated a larger chamber pressure than the booster charge, i.e., combustion was initiated in all cases.

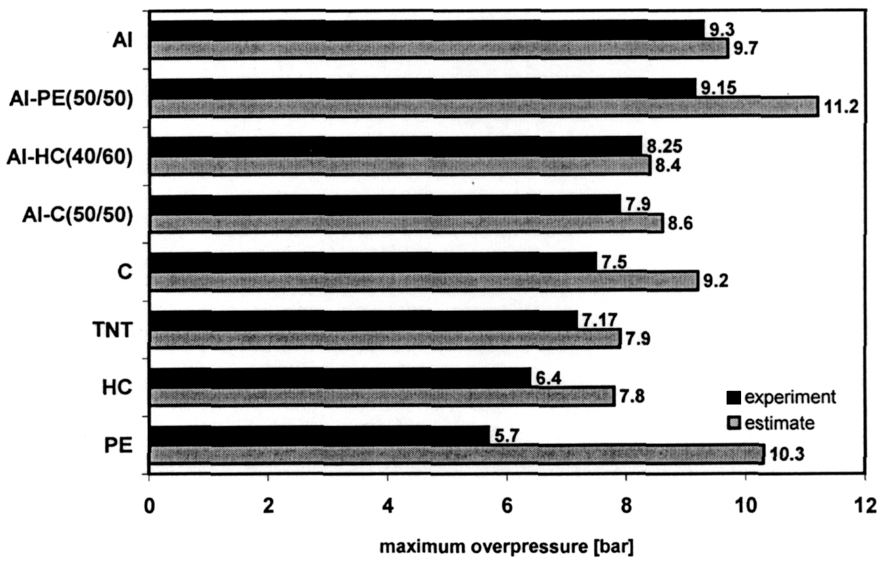

Figure 6
Summary of the final quasi-static overpressure levels found in experiments with diverse SDF charges in the 6.6-l cylinder. Theoretical estimates on the basis of a constant-volume explosion are included in gray. The entry TNT denotes no SDF charge, but a composite TNT charge with a solid shell of 1 g TNT.

Theoretical estimates on the basis of a constant-volume explosion are included in Figure 6. The theoretical maximum overpressure was not realized for all SDF charges. Especially the filling with pure PE-granulate gave too low a value, most probably due to incomplete combustion. One reason might be found in the large particle size.

Large differences between the shock-dispersed fuels could be found in the dynamics of the pressure rise. This is exemplified in Figure 7 showing low-pass filtered pressure-time histories for four different fuels. The charge with aluminum filling exhibited the fastest rise. A charge filled with carbon powder showed a completely different behavior: the pressure rise starts very slowly, accelerates with time and peaks as late as 25 ms after the detonation. In repeated tests with carbon we also found considerable scatter in the rise times; in one test it took about 40 ms to attain the maximum overpressure. Substituting 10% of the carbon powder by aluminum significantly enhanced the pressure rise rate: it shifted the occurrence of the peak pressure down to about 10 ms. For pure polyethylene granulate the pressure rise is initially fairly strong, but soon decelerates, an effect that might be explained by the particle size distribution: the fraction of smaller particles might be ignited more readily than the fraction of large particles and burn more rapidly.

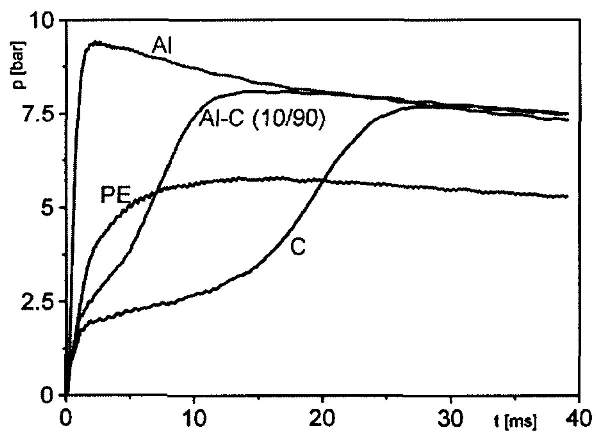

Figure 7
Overpressure vs. time for four different fillings of the SDF charges. Data are low-pass filtered at a cut-off frequency of 0.5 kHz for readability.

Another thing to note in Figure 7 is that the quasi-static overpressure slowly decreases after it has attained its maximum value. The effect is most pronounced for the SDF charge containing aluminum. This decrease reflects the fact that the content of the cylindrical steel vessel is no adiabatic system, but loses heat to the wall. Thus the average temperature and, in consequence, the average pressure decrease. If the combustion takes longer time the heat losses have to be taken into account since they counter the pressure rise due to the heat release. In such circumstances some differences between the theoretical estimates and the experimentally observed pressure values have to be expected.

Tests in a Cylindrical 40.5-l Vessel

A couple of tests were repeated in a cylindrical vessel of 40.5-l volume. The dimensions of this cylinder are about twice the dimensions of the 6.6-l cylinder: the diameter is 369 mm, the height 379 mm. Thus the typical frequency of the shock reverberations in the vessel is smaller and the products/fuel clouds can expand further. In addition, the larger volume inevitably calls for lower levels of the quasi-static pressure. Figure 8 gives a summary of the observed levels for different SDF charges. Only charges containing aluminum flakes yielded pressure levels in excess of the level caused by a composite TNT charge. Fillings of pure sucrose and carbon powder did not give any additional energy release beyond that from the booster charge, so we have to assume that ignition essentially failed. The performance of PE was again far from the theoretical expectation.

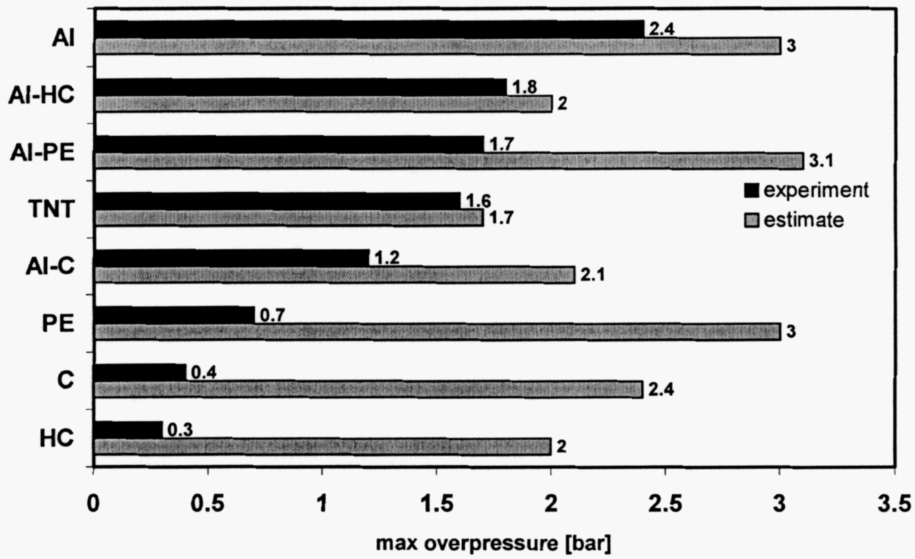

Figure 8
Summary of the final quasi-static overpressure levels found in experiments with diverse SDF charges in the 40.5-l cylinder. Theoretical estimates on the basis of a constant-volume explosion are included in gray. The entry TNT denotes no SDF charge, but a composite TNT charge with a solid shell of 1 g TNT.

Apparently the combustion in the 40.5-l cylinder has been in general less complete than in the 6.6-l vessel. In addition, it took longer periods to establish the maximum in the quasi-static overpressure. Figure 9 exemplifies this for the SDF charge containing aluminum flakes. The pressure rise rate is appreciably lower in the 40.5-l cylinder, especially towards the end of the apparent combustion period. The same effect was found in the studies on TNT after-burning. Figure 10 shows two diagrams from this study. Tests with composite charges were performed for two cases: the vessels filled with air at ambient pressure or – to inhibit after-burning – with nitrogen. The plots do not only show the additional overpressure generated by after-burning, but also give an idea about the pressure rise rate, which is significantly slower in the 40.5-l cylinder. This decrease of after-burning rates with increasing linear dimensions has also been found in numerical simulations [6].

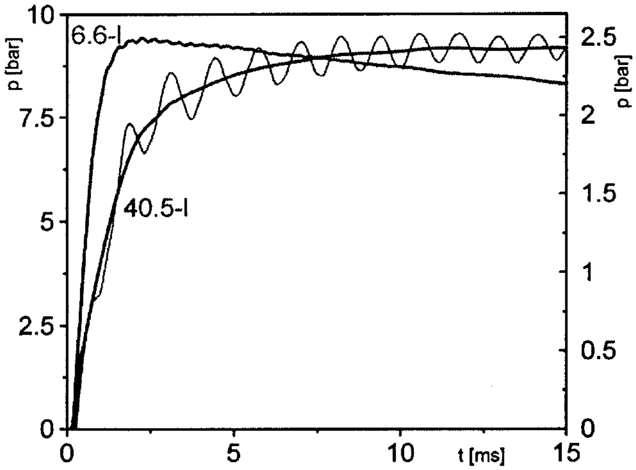

Figure 9
Development of the overpressure in the 6.6-l cylinder (left pressure scale) and the 40.5-l cylinder (right scale). Detonation of SDF charges containing 1 g aluminum flakes. Data low-pass filtered at a cut-off frequency of 0.5 kHz. Due to the lower reverberation frequency in the 40.5-l cylinder pressure oscillations are not completely oppressed in the record. Thus an interpolated curve is included.

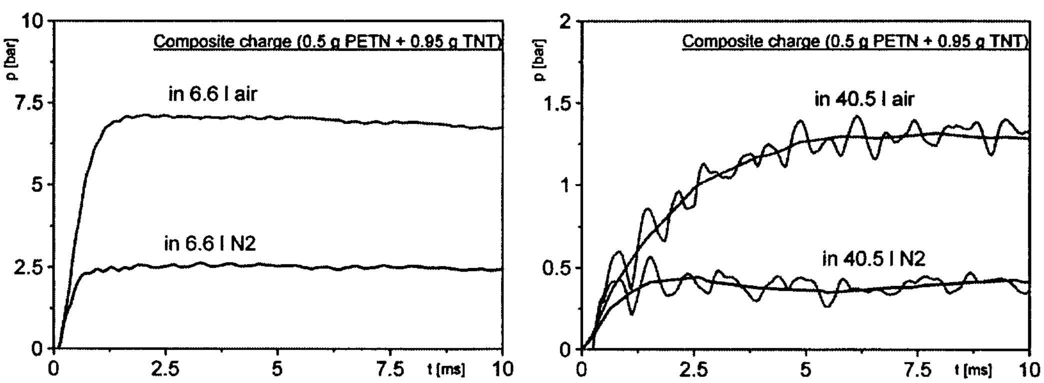

Figure 10
Development of the overpressure in the 6.6-l vessel and the 40.5-l vessel for composite TNT charges detonated in air or in nitrogen. Data filtered at a cut-off frequency of 0.5 kHz. Interpolated curves are included for the 40.5-l vessel.

Experiments in a Tunnel Model

Recently first experiments on SDF charges have been performed in a small-scale model of a closed tunnel section. The section is approximately 3 m long and has a cross-section of 80 mm x 80 mm. In this model completely different dynamics of the blast wave propagation evolve. In the tests the charges were located near one end of the tunnel at x = 1 D (D denotes the transverse tunnel dimension of 80 mm). Blast reflections from the sidewalls, the floor and the roof are of importance only close to the charge location (x < 7D) By the time the waves reach x ≈ 7D they coalesce into a unique, quasi-one-dimensional wave front. After about 4 to 5 ms, depending on the charge mass, the front arrives at the far end of the tunnel, is reflected and propagates back to the front end of the tunnel. Here the whole process is repeated in reverse direction. This oscillation continues for at least 100 to 150 ms while the strength of the blast front slowly decreases.

A comparison between the detonation of a bare booster charge and an SDF charge containing 1 g aluminum flakes showed significant effects due to combustion-released energy. In the confinement of the tunnel these effects can even catch up to the front of the blast and increase the peak pressure and the overpressure impulse of the blast wave. Figure 11 shows a plot of the peak pressure vs. range for three charges: the bare booster (0.5 g PETN), a spherical charge of 1 g PETN and the SDF charge containing 1 g aluminum. Close to the charge location the peak pressure from the SDF charge is lower than the pressure from the booster, but further down the tunnel the peak pressures soon increase to values that are equivalent to those generated by a 1 g PETN charge.

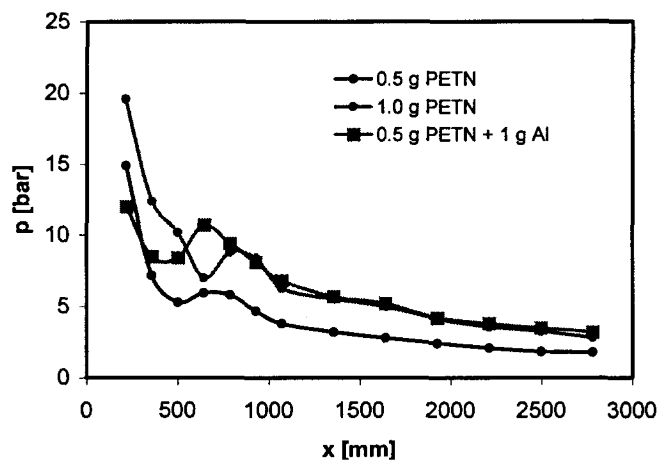

Figure 11
Peak pressure vs. range in the 3 m long tunnel model for spherical PETN charges of 0.5 g and 1 g and an SDF charge with 1 g aluminum.

After about 4 ms the blast arrives at the far end of the tunnel. Reflected peak overpressures and overpressure impulses at a gage in the end-wall have been inspected for a number of different charges. We found that the effect from the SDF charge is approximately equivalent to the effect of a composite PETN-TNT charge with a shell of 0.7 g TNT. In contrast, the same SDF charge was found to be more efficient than a composite charge with a shell of 1 g TNT in the cylindrical vessel with an L/D-ratio around 1. Presumably the mixing is less efficient in a tunnel since the tunnel walls not only give rise to a quasi-one-dimensional wave front, but also constrain the mixing of the fuel with air to be quasi-one-dimensional along the tunnel axis.

Summary

The experiments show that shock-dispersed fuels will combust in many cases. They are most effective in narrow confinements, where shock reverberations enhance the mixing between fuel and air, which is an important parameter controlling the burning rate. The largest effects were observed for fuels that consist or at least contain an appreciable amount of aluminum flakes. This might in part well be due to the size and form of the flakes. In terms of the quasi-static overpressure obtained in the chambers 1 g of the aluminum flakes excels 1 g of TNT. Nevertheless, a sufficient supply of air is a prerequisite for combustion to become effective. Thus in too small a confinement lack of oxygen can terminate the energy release prematurely.

Larger confinements in some cases caused a failure to ignite the fuel. The current hypothesis is as follows: the detonation products cloud and the dispersed fuel cloud can expand further and thus cool beyond the ignition threshold, before blast reflections from the walls can provide sufficient mixing with the ambient air. The details nevertheless depend also on the fuel: aluminum flakes or a mixture of aluminum flakes and sucrose yielded overpressure levels close to the theoretical limit even in the 40.5-l vessel. Thus it has to be analyzed whether the poor performance of polyethylene for example correlates to the properties of the substance itself or to the size and shape of our test specimen.

The above holds for confinements, where all linear dimensions are of the same order of magnitude. In a tunnel-like geometry different dynamics evolve. The blast wave in the tunnel soon develops into a unique, quasi-one-dimensional front. It could be demonstrated for an SDF charge containing 1 g aluminum flakes that the combustion-released energy feeds into the peak pressure and overpressure impulse of the wave. Completeness and rapidity of the energy release have yet to be analyzed in more detail, but the first results on aluminum indicate that SDF charges are less efficient in a tunnel.

References

[1] Ornellas, D. L., Calorimetric Determination of the Heat and Products of Detonation for Explosives: October 1961 to April 1982, Lawrence Livermore National Laboratory, UCRL-52821, Livermore, CA, 1982.

[2] Neuwald, P., Reichenbach, H., and Kuhl, A. L., After-burning of Nitropenta Products in a Calorimeter, *17th Int. Colloquium on Dynamics of Explosions and Reactive Systems*, Heidelberg, ISBN 3-932217-01-2, 1999.

[3] Neuwald, P.; Reichenbach, H. and Kuhl, A. L.; Combustion of Shock-Dispersed Fuels in a Chamber, *11th Int. Symp. on Interaction of the Effects of Munitions with Structures*, Mannheim, Germany, May 5-9, *2003.*

[4] Lewis, B. and von Elbe, G.; Combustion, Flames and Explosions of Gases, Academic Press, New York 1961.

[5] Kuhl, A: L.; Howard, M. and Fried, L.; Thermodynamic Model of Afterburning in Explosions, *34th Int. Conf. ICT, Energetic Materials*, Karlsruhe, Germany, June 24 –27, 2003.

[6] Kuhl, A. L.; Ferguson, R. E.; Oppenheim, A. K.; Sum, T-H. J.; Reichenbach, H.; Neuwald, P. Effects of Confinement on Combustion of TNT Explosion Products in Air, *9th Int. Colloquium on Dust Explosions, (part of the 3rd International Symposium on Hazards, Prevention, and Mitigation of Industrial Explosions)*, Tsukuba-Ibaraki, Japan, 23-27 October 2000.